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ULTIMATE PERFORMANCE OF THE FIXED-BEACON POSITION-FINDING SYSTEM

G. B. Rachet and J. L. Pieplu

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16. Abstract

The results obtained from analyzing the ultimate performance of the Eole position-finding system for fixed beacons are presented in synthesis. With the use of up-to-date equipment (Baker Nunn cameras) and sophisticated programming, this performance was shown to be 250 meters for distance measurements and 10 centimeters per second for Doppler measurements. After correction of distance skews the position-finding accuracy is 100-150 meters for position-finding skew and 250-300 meters for the dispersion sigma with respect to this skew.

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* INTRODUCTION

The purpose of this report is to provide a brief synthesis of the results obtained from analyzing the ultimate performance of the Eole position-finding system for fixed beacons.

This analysis was conducted, starting in March, 1972, by the Orbital Calculation Department of the Mathematics and Processing Division in conjunction with the Space Geodesics Research Groups (GRGS). The details of each of the studies will be published as technical reports, now being written.

1. EQUIPMENT USED

The analysis of the ultimate performance of the Eole position-finding system was conducted,

- Using the data collected without particular precautions from the oceanographic beacons of the LMD when they were stored on land at Victoria, British Columbia, from December 14, 1971, through January 15, 1972;
- and using the data collected during the Aureole project from May to June, 1972, a project proposed by the GRGS with the objective of simulating dialog.

This project set up five fixed beacons in France and an observation program on the Eole satellite using Baker Nunn tracking cameras, Smithsonian Astrophysical Observatory [1].

2. SHOWING THE CRITICAL PARAMETERS INVOLVED IN PRECISE POSITION-FINDING OF FIXED BEACONS

The analysis of the most important parameters in the Eole position-finding system permitted the following chief influences to be shown [2]:

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- Pass geometry (trace distance)
- Orbitography
  - accuracy altitude-wise
  - accuracy perpendicular to the plane of the orbit
  - accuracy along the trajectory
- Beacon altitude error
- Measuring satellite/responder distance
- Distribution of measurements during the pass.

The other parameters (dating measurements, Doppler measurements) were ascertained and processed with no major difficulty for the operational Eole system.

Among the parameters shown in this way, only the pass geometry and, to a lesser extent, the accuracy of distance measurement were studied in detail in the project definition phase.

It thus seemed necessary to make a more accurate evaluation of the quality of the other parameters and to define their influence on the results of position-finding.

The study dealt chiefly with orbitography and the systematic errors in distance measurement, these being the only parameters which could be improved by analysis as the distribution of measurement during a pass were generally set in advance by the remote indication programming.

3. ACCURACY OF ORBITOGRAPHY

3.1 Operational Orbitography

The Eole operational processing system uses orbitography based on a simplified model and interferometry measurements from Kourou and Pretoria only (estimate accuracy: one minute of an arc).

During the measurement period, the orbit errors could thus reach:

1.7 km along the trajectory

0.8 km altitude-wise

1.2 km perpendicular to the plane of the orbit.

Moreover, due to atmospheric friction, not taken into account in the operational system, the error along the trajectory increased sharply with extrapolation, reaching:

2.0 km after 24 hours

3.0 km after 48 hours

5.0 km after 72 hours.

3.2 Orbitography with an Accurate Model and the Same Observations

Processing of interferometer measurements with a very sophisticated forcing model (complete ground potential, atmospheric friction model, sun-moon attraction) which was very sophisticated but costly in computer time and thus difficult to integrate into operational processing, leads to the following maximum errors:

600 to 700 m along the trajectory

300 and 500 m altitude-wise and perpendicular to the plane of the orbit.

It should be noted that with more interferometer stations of the same accuracy (minitrack system for example) these figures could be reduced to 500 m and 300 m respectively as the orbit would be better covered.

3.3 Orbitography with a Complete Model and Accurate Optical Observations with the Baker Nunn Camera System

When the Baker Nunn cameras from the SAO were added in May-June 1972 (Aureole Project) the orbits could be calculated still more precisely, although the quality of these observations failed to come up to expectations (6 to 8 instead of 2 to 4 seconds of an arc).

Comparison between successive overlapping orbits shows that the residual errors are:

- along the trajectory: 120 m to 1σ (300 m maximum)
- altitude: 20 m to 1σ (50 m maximum)
- perpendicular to the plane: 25 m to 1σ (60 m maximum)

This residual error may be largely due to errors on the models used, particularly because of the resonance of the Eole orbit with the 14th order terms of ground potential; this resonance effect causes an orbital perturbation along the trajectory of period 9.2 days and amplitude about 1 km, which is difficult to take into account due to uncertainties as to the numerical value of the 14th order coefficients in developing ground potential in spherical harmonics.

4. DATING ERROR - LONG-TERM OSCILLATOR STABILITY

The search for systematic errors in the elementary data is necessarily linked to that of the dating error.

The various sources of error (satellite, propagation duration, processing) were analyzed. As a result, dating an elementary measurement on an earth time-scale (that in which the ephemeris of the satellite is given) is done to better than 50 ms, which was substantially sufficient for operational needs. In this study, which seeks the ultimate system performance, the major part of this error was corrected and we can estimate that dating is better than 5 ms.

Comparison of the on-board time-scale (materialized by the rhythm of beacon interrogation) to an earth atomic time-scale enabled long-term stability of Eole's ultra-stable oscillator to be achieved [3].

An eighteen-month analysis of the comparison points gives the following result:

linear drift per day $\frac{F_1}{F_0} = 7.5 \cdot 10^{-11} \pm 0.3 \cdot 10^{-11}$

quadratic drift $\frac{F_1}{F_0} < 10^{-13}/\text{day}^2$

5. ACCURACY OF ELEMENTARY DISTANCE AND DOPPLER MEASUREMENTS

5.1 Introduction

This study deals with the data collected during the Aureole project, particularly those obtained when the 5 beacons were at the same point, on the roof of the Gay Lussac Building in Bretigny.

For this period we had about fifteen passes common to all five beacons with a high interrogation density (one measurement every ten seconds per beacon).

The location of the beacons enabled relative systematic errors connected with the beacon electronics to be isolated, the other systematic errors (satellite, propagation, orbit, beacon position) being eliminated for one and the same pass.

5.2 Method

The orbitography calculations, the results of which are presented in Section 3, enable the position of the satellite to be determined at the moment of each Eole measurement, at a reference point connected to the ground. We also know the position of the beacons at this same reference point, based on the classic geodesic survey. We then deduce a distance and a reference Doppler to be compared to the actual measurements.

Taking into account the orbitography and beacon-position errors, this reference amounted to 200-300 m over distance and about 1 m/sec on the Doppler. These errors, systematic for one pass, are randomly distributed on other passes.

5.3 Systematic Errors for Distance Measurement

The deviations on one pass between actual measurement and reference are generally not centered, which could be due to skews introduced by the reference, the propagation, etc. We determine an average skew per pass and per beacon. Figure 1 gives these average systematic errors on distance for one beacon and for all the passes observed.

We find that the average deviations found at each pass are distributed around a non-zero value, which cannot come from the orbit or beacon-position references, in view of the geometric variety of the passes.

For the beacon considered, the average deviation seems to vary from 300 to 400 m over six observing days, but as the σ of each point is on the order of 200 m we are at the limit of accuracy.

Figure 2 shows the distribution of these average values for another beacon for a slightly longer period, overlapping the previous period. Such a variation is not noted.

The table below gives, for each beacon, the average value of this correction over all the passes observed, and the interval of confidence (1σ) for this determination.

Beacon number	Average skew ref-observed (m)	σ(m)	Time correction beacon transit (m)
4	-780	270	-750
7	10	230	-360
9	390	190	-150
12	-580	150	-790
13 first period	500	130	-470
13 second period	500	170	-470

The measurements processed received, in the operational system, a standard beacon transit time correction. A measurement of this correction was done for each beacon before the Aureole experiment. The deviations from this standard correction are shown in the table above.

The direction of this correction is such that it must be added algebraically to the distances coming out of the operational system.

The difference between the value found on the ground and that found by this "staggering" in flight amounts to 1000 m (beacon 13).

Finally, it should be noted that for one of the five beacons this beacon transit correction time varied from 500 to 1000 m during the satellite pass.

5.4 Random Errors on Distance and Doppler Measurements

The noise level of the measurements was attained by two different approaches.

- either as a by-product of the search for systematic errors (adjustment of time skew, distance, altitude, etc. on the deviations of measurements from the reference orbit),
- or by using a "short arc" technique where certain orbit parameters (average movement, inclination, etc.) are adjusted pass by pass.

We find the following values at 1σ

Distance	Doppler
σ = 250 m	σ = 1 m/sec

These values are only slightly affected by the linkage balance, at least by satellite elevation angles greater than 15°.

6. ULTIMATE ACCURACY OF THE POSITION-FINDING SYSTEM

Determination of station position is done for each pass. We determine only the latitude and longitude of the station: the height is fixed at the value of the geodesic survey.

The reference orbit is that obtained with accurate optical measurements. The calculations were performed with and without the systematic correction for distance determined in the "evaluation" section. The locations for each pass of one beacon are given in Figure 3.

We note that:

- the average position is not substantially improved (that corresponding to the cloud without correction is already in the σ of the cloud after correction). This comes from the good geometry of the passes as a whole.

- A great deal is gained on the σ of the determination when the correction is made, which is a good confirmation of the validity of this value.

The table below shows the results with respect to the reference point from the survey, and the σ of the dispersion clouds obtained for each beacon at the first and second observation period (beacons grouped in Bretigny then dispersed through France).

FIRST LOCATION

BEACON NUMBER	1st OR 2nd OBSERVATION PERIOD	DEVIATION FROM REFERENCE POINT (m)	σ(m)	DISTANCE CORRECTION	REFERENCE ORBIT
4	1	480	760	0	potential at end of interferometer measurements
7	1	250	600	-	
9	1	240	670	-	
12	1	400	850	-	
13	1	170	720	-	
13	2	200	400	-	
4	1	250	640	0	potential at end of accurate optical measurements
4	2	120	540	-	
7	1	80	170	-	
7	2	170	300	-	
9	1	120	290	-	
9	2	150	200	-	
12	1	130	620	-	
13	1	230	490	-	
13	2	220	330	-	
4	1	100	300	-784	
4	2	70	250	-784	
7	1	80	170	12	
7	2	140	290	12	
9	1	110	380	390	
9	2	170	260	390	
12	1	80	260	-583	
13	1	130	310	505	
13	2	180	300	505	

Here we find that;

- the utilization of accurate optical measurements for orbitography enables us to gain a factor of 2 on the deviation between the mean point and the reference point; going from a deviation of 300-400 m to one of 150-250 m;
- the sigma is also improved, but unequally from one beacon to another;
- the application of the distance error improves the distance to the reference point only slightly;
- the dispersion cloud is reduced by a factor of 2 by this correction;
- the correction determined on the measurements of the first observation period and applied to the measurements of the second period gives coherent results as to the two periods.

To summarize, we may retain the following values representing the ultimate position-finding accuracy of the system:

- probable position-finding skew: 100-150 m
- dispersion with respect to this skew: 250-300 m

We should recall that these results apply to fixed beacons and cannot be considered valid for moving beacons, even slightly moving, as buoys and ships.

7. CONCLUSIONS

This study enabled us to find the ultimate performance of the Eole from an orbitography giving 300 m along the trajectory and 50 m perpendicularly.

- the noise of the distance measurements is compatible with what had been expected for the system; that of the Doppler measurements is clearly less:

distance	250 m
doppler	10 cm/sec

- the distance skew is found with accuracy better than 200 m, showing up distances that can reach 1000 m with beacon transit time measurements made on the ground. This confirms, for the Dialog project, the great importance of precise laser reference measurements for evaluation of the "flight" configuration data of the system.

- after correction of these distance skews, the position-finding accuracy is then:
  - probable position-finding skew: 100-150 m;
  - dispersion (σ) with respect to this skew: 250-300 m;
- It must be emphasized that the above figures, valid for fixed beacons, can be attained only by substantial observational equipment (here, Baker Nunn camera system) and expensive computing (sophisticated forcing models).

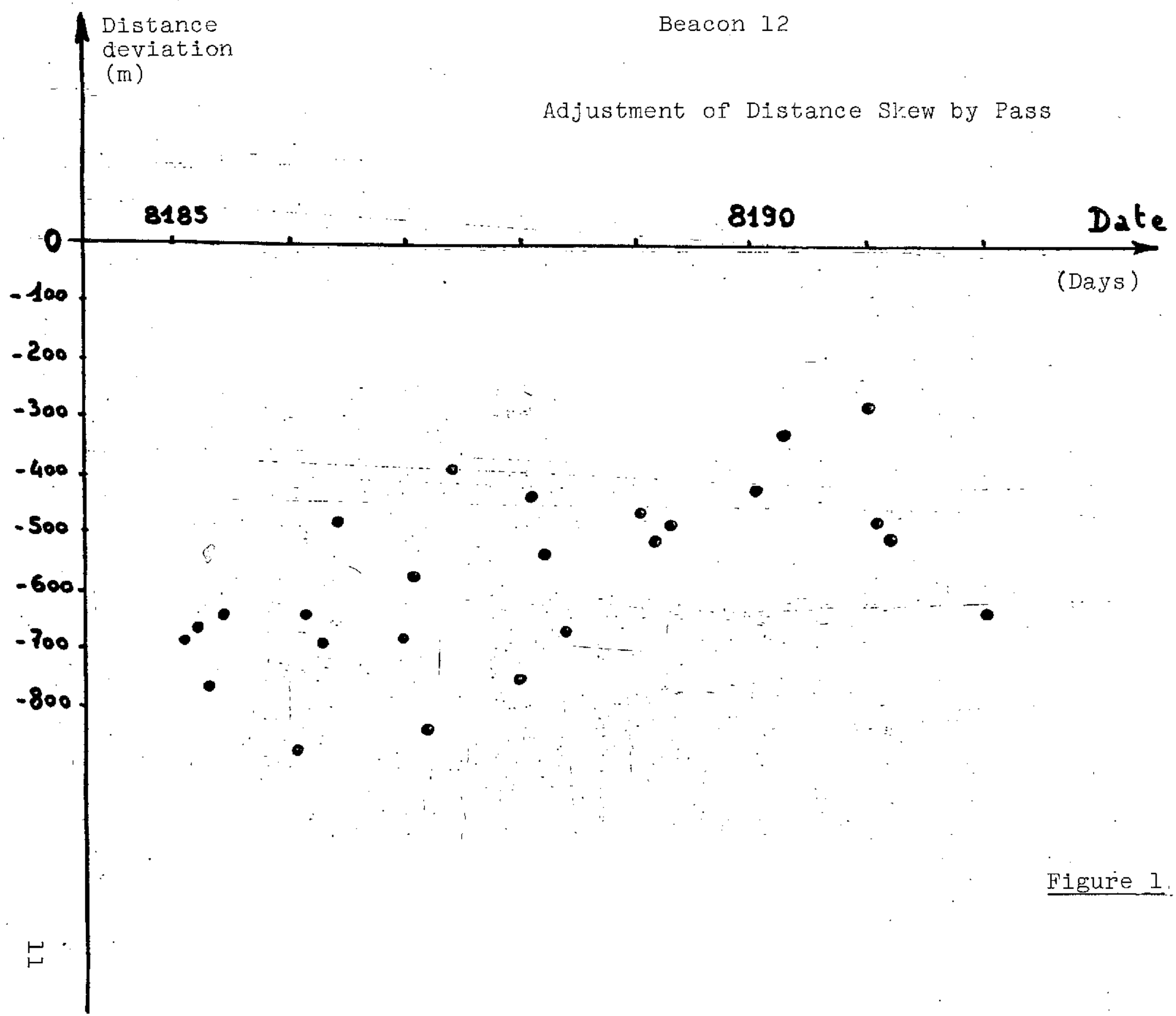

Beacon 12
Adjustment of Distance Skew by Pass
Distance deviation (m)
0
-100
-200
-300
-400
-500
-600
-700
-800
8185
8190
Date
(Days)

Figure 1

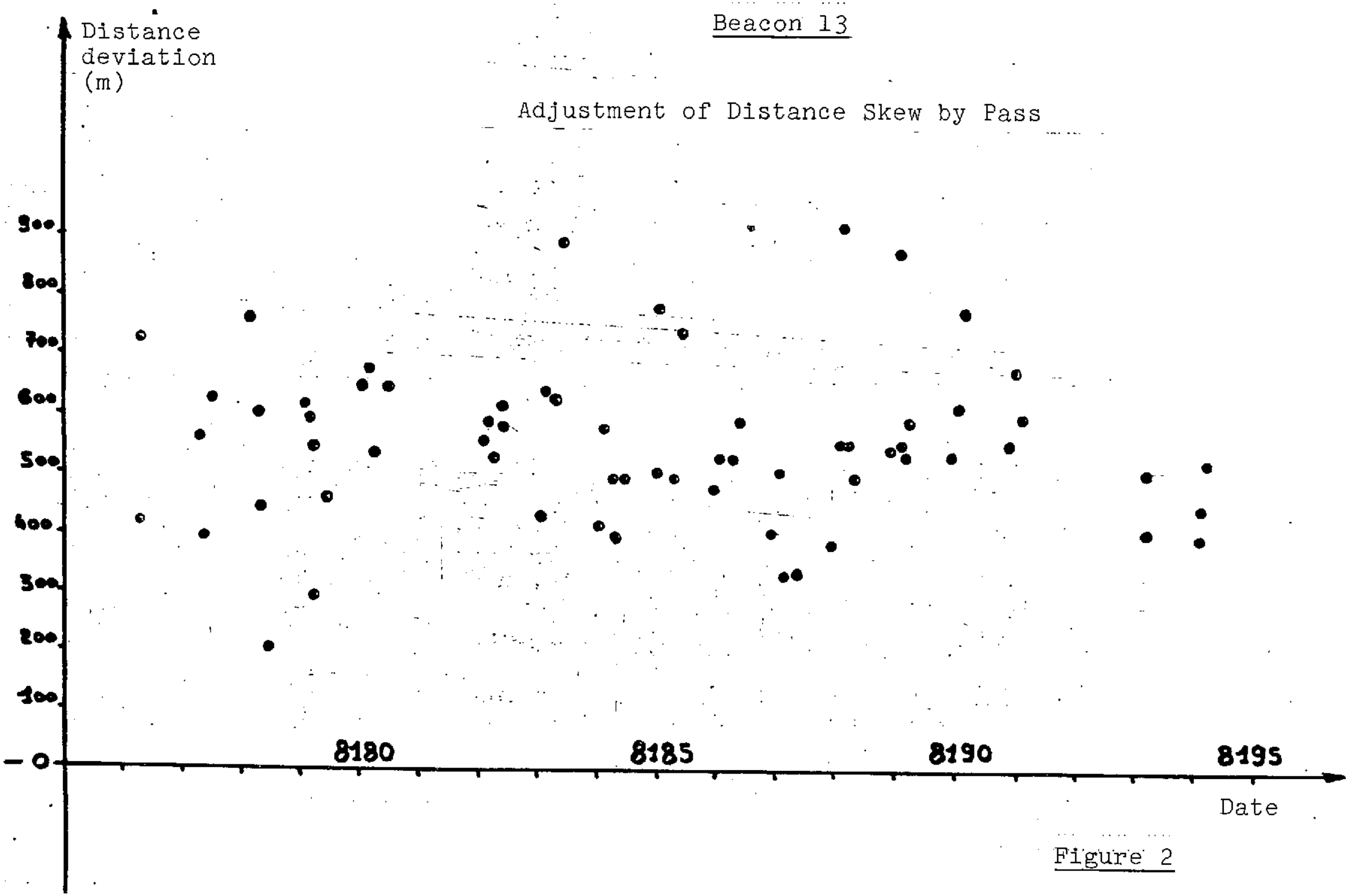
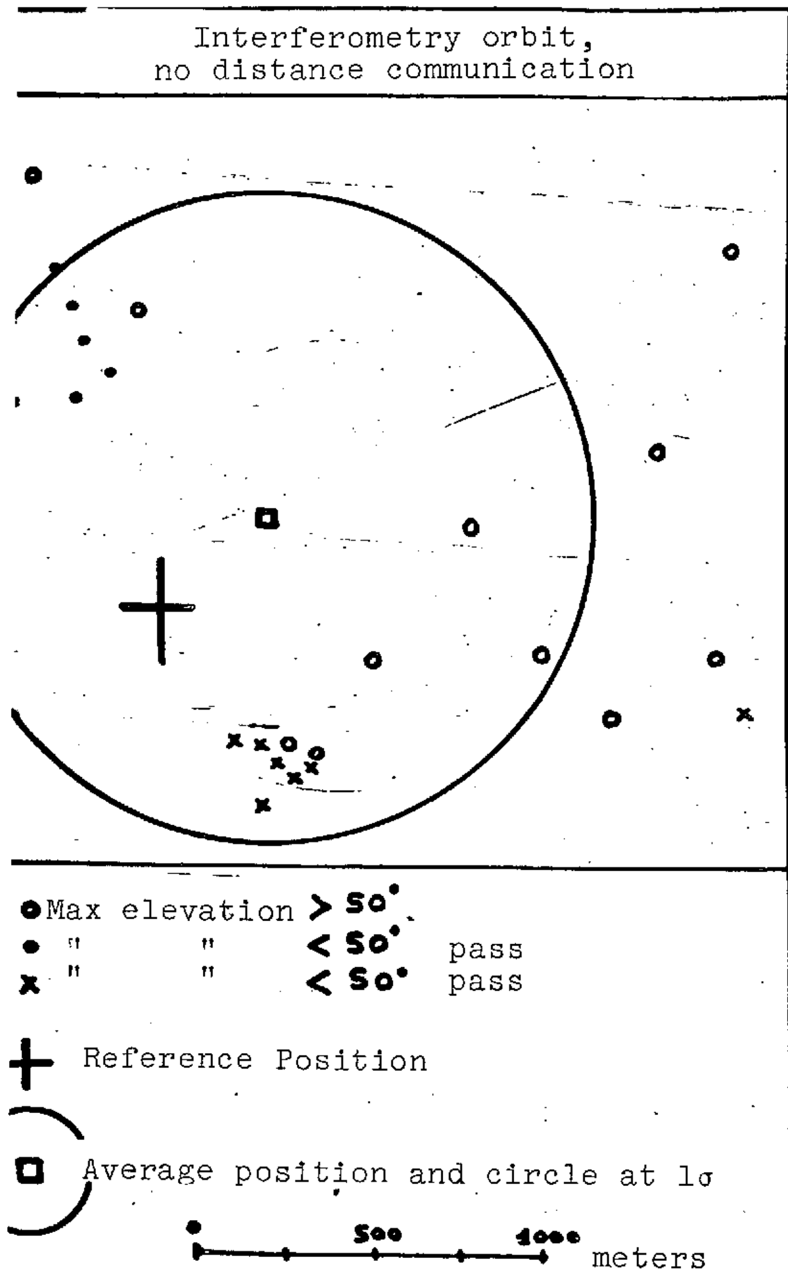

Beacon 13
Adjustment of Distance Skew by Pass
Distance
deviation
(m)
900
800
700
600
500
400
300
200
100
0
8180
8185
8190
8195
Date

Figure 2

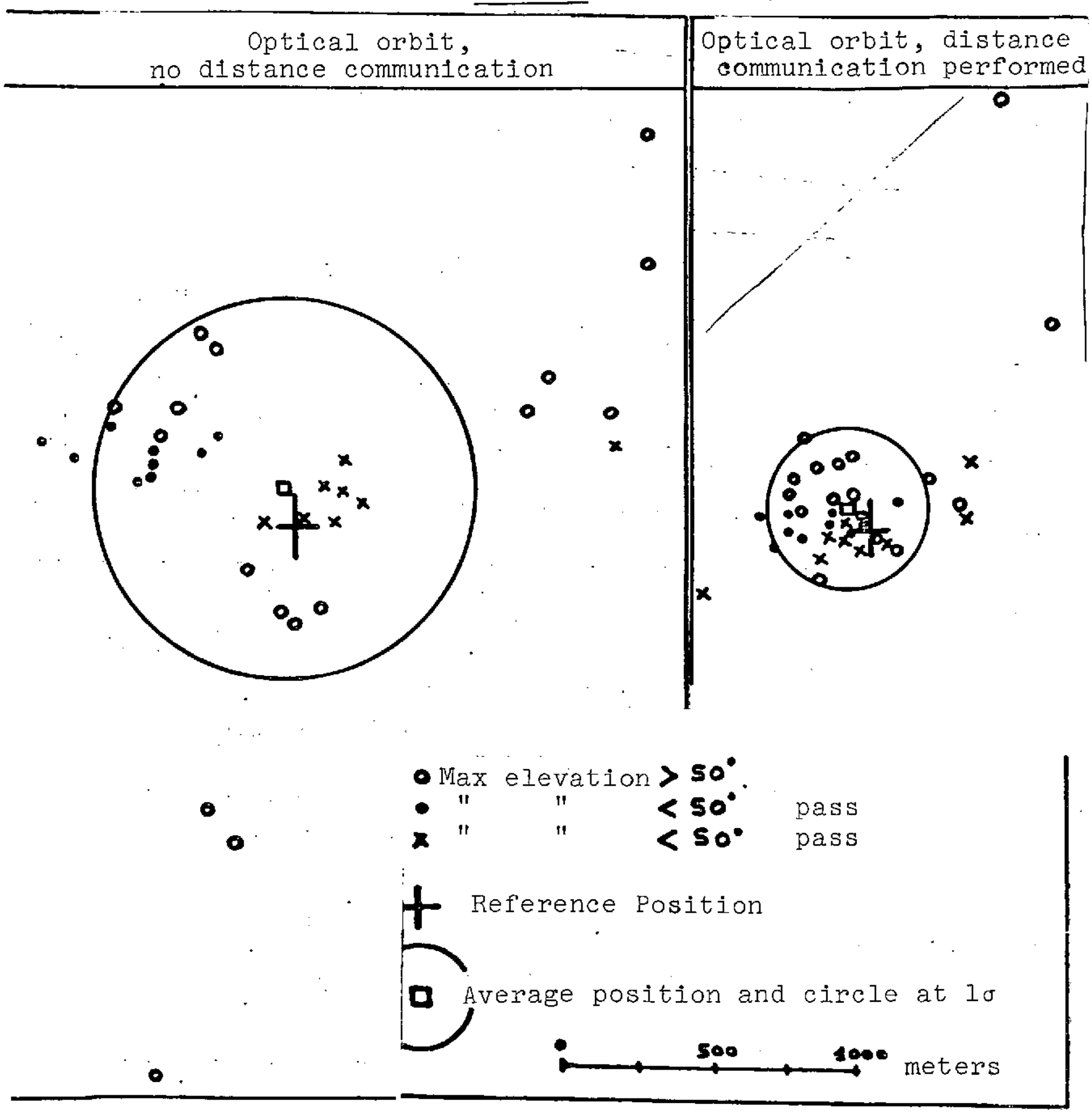
AUREOLE



Beacon 12 1st period. Distribution of locations on 1 pass.

Figure 3

AUREOLE (Continued)



Beacon 12 1st period. Distribution of locations on 1 pass.

Figure 3 (Continued)

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